

Reverse Rotation of the Accretion Disk in RW Aur A: Observations and a Physical Model

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Abstract

Speckle interferometry of the young binary system RW Aur was performed with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences using filters with central wavelengths of 550 nm and 800 nm and pass-band halfwidths of 20 nm and 100 nm, respectively. The angular separation of the binary components was $1.448'' \pm 0.005$ and the position angle of the system was $255.9^\circ \pm 0.3$. at the observation epoch (JD 2 454 255.9). We find using published data that these values have been changing with mean rates of $+0.002''/\text{yr}$ and $+0.02^\circ/\text{yr}$, respectively, over the past 70 years. This implies that the direction of the orbital motion of the binary system is opposite to the direction of the disk rotation in RW Aur A. We propose a physical model to explain the formation of circumstellar accretion disks rotating in the reverse direction relative to young binary stars surrounded by protoplanetary disks. Our model can explain the characteristic features of the matter flow in RW Aur A: the high accretion rate, small size of the disk around the massive component, and reverse direction of rotation.

Introduction

T Tauri stars are young ($t < 10^7$ years), low-mass ($M \leq 3 M_\odot$) stars in the stage of gravitational contraction evolving toward the main sequence. Young stars whose activity is due to the accretion of matter from surrounding protoplanetary disks are classical T Tauri stars (CTTS) [1]. Most CTTS are members of binary and multiple systems [2], some of which are surrounded by extended ring-like envelopes, i.e., outer (protoplanetary) disks. It is difficult to observe the inner regions of protoplanetary disks bounding the components due to the small angular sizes of such systems.

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Although it has long been possible to obtain structural images of the outer parts of the protoplanetary disks in some T Tauri systems [3, 4], the structure of the inner parts of these disks has only recently been imaged for a few wide binary systems [5, 6]. The observations indicate that an area of decreased density with a complex flow structure including a circumstellar accretion disk forms in the inner parts of the protoplanetary disks surrounding young T Tauri stars.

The flow of matter in binary systems accreting material from protoplanetary disks has been simulated numerically in many studies [7–17]. The simulation results indicate the following major flow elements in these systems: circumstellar accretion disks around the system components, a rarefied area in the central parts of the protoplanetary disk adjoining the binary, and a complex system of gas-dynamical flows. The analysis of calculation results [14–16] indicate that the supersonic orbital motion of the system components through the gas of the protoplanetary disk leads to bow shocks formation ahead of the circumstellar accretion disk of each component; these bow shocks predominantly determine the dynamics of the matter in the area of decreased density in the central part of the protoplanetary disk, as well as accretion processes in the system. The results of numerical simulations agree well with the observed flow morphologies for systems whose inner structure is resolved. However, at least one young binary, RW Aur, is known to have flow structures that seem to differ principally from the results of currently available numerical simulations.

RW Aur is in the original list of T Tauri stars compiled by Joy [18] in 1945. One year earlier, the companion RW Aur B was discovered near the primary star RW Aur A at a separation of $1.2 - 1.3''$ [19]. Since the distance to RW Aur is 140 pc [20], the separation between the components exceeds 170 AU, even projected onto the celestial sphere. According to [21], the mass of RW Aur A is $1.3 - 1.4M_{\odot}$ and the mass of RW Aur B $0.7 - 0.9M_{\odot}$. Both components are CTTS; according to [22], the accretion rate onto RW Aur A is $\sim 3 \times 10^{-7} M_{\odot}/\text{yr}$, and the accretion rate onto RW Aur B a factor of ten lower.

A bipolar jet is observed from RW Aur A [23–25]. Interaction between this jet and the surrounding gas can be traced to distances of $\sim 4.6 \times 10^4$ AU [26]. Arguments suggesting that the jet is inclined to the line of sight by $45^{\circ} - 60^{\circ}$ are given in [21].

A submillimeter image of the vicinity of RW Aur with high angular resolution was obtained in [21]. Analysis of the observational data indicates that RW Aur A is surrounded by an axially symmetric gas–dust disk with an outer radius of ~ 50 AU. The plane of the disk is perpendicular to the jet, and the disk rotates clockwise viewed from the Earth. A spiral arm of molecular gas curved counterclockwise goes out from the disk. The length of this arm is ~ 600 AU. Molecular gas is observed around RW Aur B as well, but its complex spatial and kinematic structure make it unclear whether it forms a circumstellar disk.

It was established in [21] that the direction of disk rotation in RW Aur A is opposite to the direction of the axial rotation of the jet, which was first determined in [27]. This raised doubts about widely accepted mechanisms of jet formation in such systems. This transformed an relatively ordinary description of one particular, albeit interesting, binary system into a fundamental problem that was very important to our understanding of the physical processes in accretion disks. It was recently concluded that the true direction of jet rotation in RW Aur A cannot be determined using available observations [28]. Nevertheless, the system remains the

subject of intense research because of the opposite directions of the rotation of the circumstellar disk, which was determined with high reliability, and the possible direction of orbital motion proposed in [21]. The direction of orbital rotation was actually not measured in [21], but a particular direction was proposed to explain the formation of the observed spiral arm due to the tidal effect of RW Aur B, in accordance with theoretical considerations from [29].

Determining whether or not the system has a unique reversed disk requires direct determination of the direction of orbital rotation of the RW Aur binary system. This paper presents observations indicating that the angular rotation of the disk in RW Aur A and the orbital angular momentum of the system are indeed opposite, i.e. the disk rotation is reversed. The results of three-dimensional, gas-dynamical numerical simulations lead us to suggest a physical model to explain the formation of reversed accretion disks in young binary stars surrounded by protoplanetary disks.

1 Observations

Speckle interferometry of RW Aur was performed with the 6-m telescope of the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences on the night of December 15–16, 2011. A system of speckle image detection based on a CCD with internal signal amplification was used [30]. Speckle interferograms were obtained in the visible with filters having central wavelengths of 550 and 800 nm and pass-band halfwidths of 20 and 100 nm, respectively. A plane achromatic micro-objective with 16-fold amplification provided a scale of 8.86 ± 0.02 and 8.92 ± 0.02 milliarcsec per pixel at the focal plane of the telescope for the first and second filters, respectively.

The calibration of the image scales in the different filters and the angular positioning were performed using an opaque mask with two round holes placed in the beam converging from the main mirror. Observations of a bright single star using the mask enabled the detection of interference bands from the pair of apertures, which were used to derive the image scale and position angle correction from the spatial frequency and orientation of the bands. 2000 speckle images were accumulated with exposure times of 20 ms in each filter, to determine the position parameters and magnitude differences. We estimated the atmospheric seeing from the full width at half maximum averaged over a run of speckle frames for a stellar image; the seeing was $\approx 1''$, slightly less than the apparent component separation. Therefore, one-quarter of the position angle was determined using a long-exposure image of the binary.

The relative position of the components and the difference in their magnitudes were determined using power spectra averaged over a run of speckle interferograms, without correction for the atmosphere-transfer function [31]. The power spectrum for a binary star is a cosine function whose period is determined by the angular separation ρ of the components, and the band orientation by the position angle θ of the two stars. The magnitude difference Δm between the components was calculated using the band contrast in the power spectrum [32, 33].

Our analysis of speckle images obtained at epoch 2011.9580 (in Bessel years) in the 550 nm filter yielded the angular distance between the components $\rho = 1.448'' \pm 0.005$, the position angle of the binary system $\theta = 255.9^\circ \pm 0.3$, and the

Date	Filter	$\rho \pm \sigma_\rho, ''$	$\theta \pm \sigma_\theta, ^\circ$	Reference
1944.246	V	1.17	253.8	[19]
1944.248	V	1.28	254.9	[19]
1990.85	K	1.39 ± 0.03	256 ± 1.0	[35]
1994.85	U'-I'_c	1.4175 ± 0.0034	255.459 ± 0.065	[34]
1996.93	K	1.397 ± 0.026	254.6 ± 1.0	[22]
1996.93	L	1.396 ± 0.018	254.5 ± 1.0	[22]
1999.87	N	1.42 ± 0.02	254.6 ± 0.4	[36]
1999.87	IHW18	1.38 ± 0.02	254.7 ± 0.4	[36]

Table 1: Values of ρ and θ for RW Aur A+B available from the literature.

magnitude difference between the components $\Delta m = 1.88^m \pm 0.04$. The same values for the 800 nm filter are $1.445'' \pm 0.004$, $255.9^\circ \pm 0.3$, $1.43^m \pm 0.02$, respectively.

2 Interpretation of the results

The Table contains all previously measured values of ρ and θ for RW Aur in various spectral ranges available from the literature. The most accurate measurements were performed with the Hubble Space Telescope using the Wide Field Camera and Planetary Camera 2 in five filters (F336W, F439W, F555W, F675W, and F814W) corresponding approximately to the U, B, V, R_c and I_c filters [34].

We plot the time variations of ρ and θ in Figure 1, using our data and those from the Table. The dashed lines $y = kt + b$ are least-squares fits to the observations. The parameters (k_ρ , b_ρ , and k_θ , b_θ) of these lines were calculated assigning weights that were inversely proportional to the uncertainties σ_ρ and σ_θ . The first two data points in [19] do not have uncertainties; therefore, we used their mean when calculating k and b and considered the rms deviation from the mean as the uncertainty.

The coefficients k_ρ and k_θ , characterize the mean rates of variation of ρ and θ over the ≈ 68 years of observation, and prove to be $+2.0 \times 10^{-3}''/\text{yr}$ and $+2.0 \times 10^{-2}^\circ/\text{yr}$, respectively.

For a distance to RW Aur $\simeq 140$ pc, we find that the tangential component of the velocity with which the components are moving away from each other is $V_t \simeq 1.3$ km/s. If $\rho \simeq 1.4''$, the component separation projected onto the celestial sphere is $r_t \simeq 200$ AU. Assuming that the total mass of the components is $M_A + M_B < 2.3 M_\odot$ [21], the condition that the components be gravitationally bound requires that the relative velocity of their motion be no greater than

$$V_{max} = \sqrt{\frac{2G(M_A + M_B)}{r}},$$

where r is the component separation. By substituting the numerical value of r_t (which is $\leq r$) for r in this expression, we obtain $V_{max} \simeq 3.2$ km/s. This suggests that the value of V_t we have obtained is consistent with the hypothesis that the components RW Aur A and B form a gravitationally bound system.

The available data are not sufficient to determine the orbital parameters for this system. The orbital period P can be approximated using the inequality $P \geq$

$2\rho/k_\rho \sim 1500$ yr. Another estimate can be obtained from Kepler’s third law:

$$P = \sqrt{\frac{a^3}{M_A + M_B}} > 700 \text{ yr},$$

assuming that the angular size of the semi-major axis a of the orbit exceeds $1.4''/2 = 0.7''$.

Since $k_\theta > 0$, the orbiting components move counterclockwise when viewed from the Earth. Therefore, the accretion disk in RW Aur A rotates opposite to the direction of rotation of the binary system. Accordingly, this suggests reverse rotation of the accretion disk in RW Aur A.

3 A model for the formation of a reversed accretion disk

The direction of rotation of the accretion disk in RW Aur A is defined by the angular momentum of the falling matter. For reverse rotation to occur, the angular momentum delivered to the disk by the falling matter must be opposite to the angular momentum of the system. Numerical simulations of these systems have been performed in various studies [7–17], have not indicated the appearance of reversed accretion disks in binary systems for a wide range of parameters. In addition, analysis of the flow structure that forms in the vicinity of a young binary indicates that flows directed opposite to the motion of the components can exist [15]. Indeed, the velocity field presented in Figure 2 suggests that flows of matter in the area between the components of a young binary move opposite to the rotation of the circumstellar accretion disks.

The main flow elements identified in [15] are shown schematically in Fig. 3. The shaded area corresponds to the inner edge of the protoplanetary disk; the components of the system are marked M_1 (the more massive primary and M_2 (the secondary); the dark grey filled areas denote the circumstellar accretion disks, and the solid curves show the bow shocks that form due to the supersonic orbital motion of the stars through the envelope material. The dashed curves with arrows denote the directions of the matter motion. All the velocities are shown in a non-inertial coordinate system that rotates together with the binary system (counterclockwise).

Figure 3 shows that matter leaves the inner edge of the protoplanetary disk and moves toward the binary components. Sooner or later, it interacts with the bow shocks and divides into two flow families, marked **A** and **B** (Fig. 3). The matter of flow family **A** loses its angular momentum at the shock and moves into the region between the components. There, the flows collide and form a shock, which resembles a bar between the circumstellar disks. The matter of flow family **B** moves toward the inner edge of the protoplanetary disk and carries away excess of angular momentum. The bar is appreciably inclined, since the orbital velocity of the low-mass component is greater (and the bow shock is more powerful); accordingly, the flow of matter onto this component is stronger.

The size of the semi-major axis of RW Aur is not known exactly; however, it is obviously greater than ~ 200 AU, since this is the current observed component separation. We can estimate the orbital velocities of the components to be $V_A \sim 1 \text{ km/s}$ and $V_B \sim 2 \text{ km/s}$, assuming that the orbit is circular and the component masses are

$0.8M_{\odot}$ and $1.35M_{\odot}$. These estimates agree with the observed relative velocity of the components, allowing for the projection of the motion onto the celestial sphere. If the orbit is non-circular, the orbital velocities of the stars will be functions of the phase, and (if the system is not currently at apastron) they could be even smaller. The bow shocks that determine the flow structure in these systems can form only if the velocity of the components moving through the gas of the common envelope exceeds the sound speed. Assuming that the temperature of the surrounding gas is $100 \div 200K$ [21], the sonic speed is estimated to be $C_s \approx 1.0 \div 1.6\text{km/s}$. It is obvious that the velocity of the primary star in RW Aur is close to (or less than) the sonic speed. This suggests that the flow structure in this system will differ dramatically from the structure obtained in numerical simulations of the systems with supersonic motion of the components.

In the solution in which the bow shock of the primary is either absent or very weak, the matter flow due to the redistribution of angular momentum at this shock (\mathbf{A}_1 in Fig. 3) disappears, and the flow \mathbf{A}_2 going around the secondary will be completely captured by the more massive component. The flow structure in this system is shown schematically in Figure 4. The flow \mathbf{A}_2 (with angular momentum opposite to the orbital angular momentum) collides with the accretion disk of the primary, which can lead to the formation of a reversed accretion disk. Continuum observations confirm the presence of a flow connecting the components of RW Aur (see [21], Fig. 1a).

If the system is initially in a state in which one component moves with a subsonic velocity (e.g., if the mass ratio is low), the accretion disk of the primary will be reversed over the entire lifetime. Accordingly, the star will always accrete matter with negative angular momentum, and the direction of its intrinsic rotation will also be reversed. However, if we assume that the transition to a state with a reversed disk occurred not long ago, the star should still retain its intrinsic angular momentum (spin), whose direction coincides with that of the angular momentum of the system and protoplanetary disk, since the star accreted the matter with positive angular momentum before this transition.

The accretion disk in such a system will have a number of characteristic properties. The reversed rotation of the disk relative to the stellar rotation implies that the angular momentum in inner parts of the disk must partly annihilate, leading to a substantial increase in the accretion rate. This effect is especially appreciable when the star has a magnetic field (even if it is weak). Moreover, the removal of angular momentum due to annihilation should lead to an appreciable decrease in the disk size, since it is not necessary for the disk to spread to the radius of the last stable orbit defined by tidal interactions.

Analysis of available observational data confirms both these hypotheses. Indeed, according to [21], the radius of the accretion disk in RW Aur A is ~ 50 AU, which is only $\sim 60\%$ of the radius of the last stable orbit determined by Paczynski [37]. The accretion rate onto this star appreciably exceeds characteristic values for such systems, reaching $\sim 3 \times 10^{-7} M_{\odot}/\text{yr}$ [21].

Another important observational manifestation that determines the validity of the model for reversed-disk formation could be associated with the direction of rotation of the jet. As we noted above, it is currently not possible to determine the direction of jet rotation [28]. However, the formation of a reversed disk can be explained in the proposed model without violating generally accepted physical postulates, even if RW Aur A has a jet that rotates opposite to the rotation of the

accretion disk [21, 27].

Indeed, if the transition to the reversed-disk state occurred not long ago, the star should still have an intrinsic angular momentum that coincides in direction with the angular momentum of the system and protoplanetary disk. The stellar magnetic field (estimated to be $\simeq 1.5$ kGs for RW Aur A in [38]) should lead to the capture of matter at the magnetosphere boundary, accompanied by a corresponding change in the direction of rotation of the matter. This results in the formation of accretion columns, along with jets. The jets can be accelerated by traditional mechanisms in this case (see, for example, [39–44]). The rotation of the jets should coincide with the rotation of the star (and, accordingly, the system), since the jets are fed by matter captured by the magnetosphere. Therefore, the direction of jet rotation should coincide with the direction of system rotation in the proposed model, although it may well be opposite to the rotation of the accretion disk around a component.

Conclusions

Our observations and the analysis of data obtained earlier have enabled us to directly determine for the first time the true direction of orbital rotation of the RW Aur binary system. This system displays an extremely interesting feature: reverse rotation of the circumstellar disk around the massive component RW Aur A relative to the orbital motion of the binary system.

We have proposed for the first time a mechanism to explain the formation of reversed accretion disks in young binary systems surrounded by protoplanetary disks. The secondary components in some systems move in orbits with supersonic speeds relative to the gas of the circumbinary envelope, while the more massive primary components move with subsonic or approximately sonic speeds. The matter in such a system passes through the bow shock that forms in front of the secondary and divides into two flows, one of which can deliver matter with “negative” angular momentum onto the accretion disk of the primary (Fig. 4). The disk that forms in this case will rotate opposite to the orbital motion of the system and the intrinsic rotation of the star.

A system can achieve a state when one component moves with subsonic speed in several ways. First of all, the system may have been in this state initially, but with a very low component-mass ratio, as is more typical for star–planet systems than traditional binary stars. The accretion disk of the primary will be reversed in this system over the entire lifetime. The case when both components originally moved with supersonic speeds, but one slowed down at some time, is more interesting. This can occur as a result of a change in the component-mass ratio as the components accrete matter (since the accretion rate onto the more massive companion is higher [15]) or when the system approaches apastron, if the orbital eccentricity is fairly large.

Numerical simulations show that both accretion disks have positive angular momentum if the orbital motion is supersonic. As the velocity of the primary decreases to the sonic speed, its bow shock should disappear, after which its accretion disk will be fed mostly by matter with negative angular momentum. As a result, two zones can form for some time in the disk: an outer zone with reversed rotation and an inner zone with direct rotation. The angular momentum will annihilate at the

boundary between these zones, leading to an appreciable increase in the accretion rate. The characteristic time required for the disk to be transformed can be estimated using the ratio of the radius of the original accretion disk (the radius of the last stable orbit) to the sonic speed for the disk temperature. This time is $\sim 10^3$ years for RW Aur. If the system is transformed to a state with a reversed disk as a result of a changing component-mass ratio, it cannot leave this state in the future, since the component-mass ratio will only increase with time. If such a transformation occurs when the system approaches apastron, the star may demonstrate periodic bursts in the accretion rate, which are, however, difficult to observe, since all systems of this kind have long periods.

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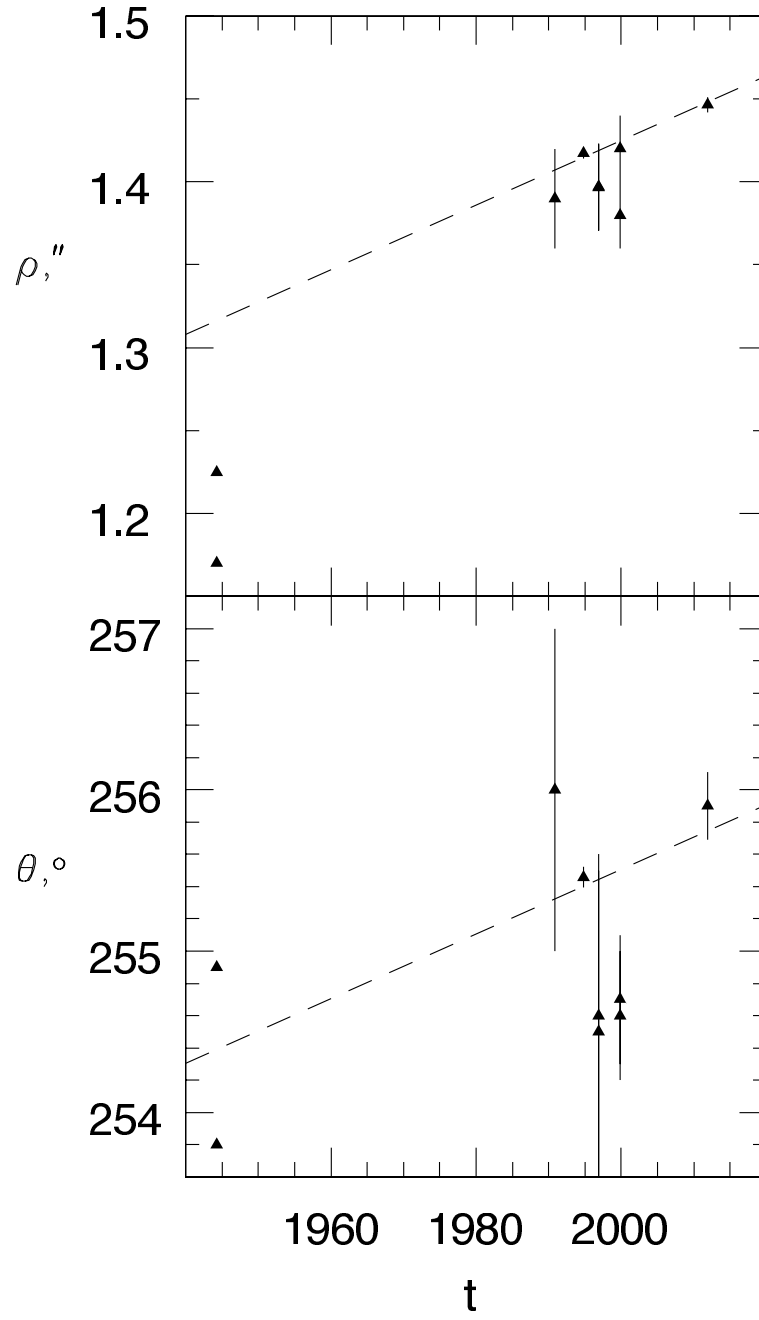


Figure 1: Angular distance between the components (above) and position angle (below) of RW Aur as functions of time.

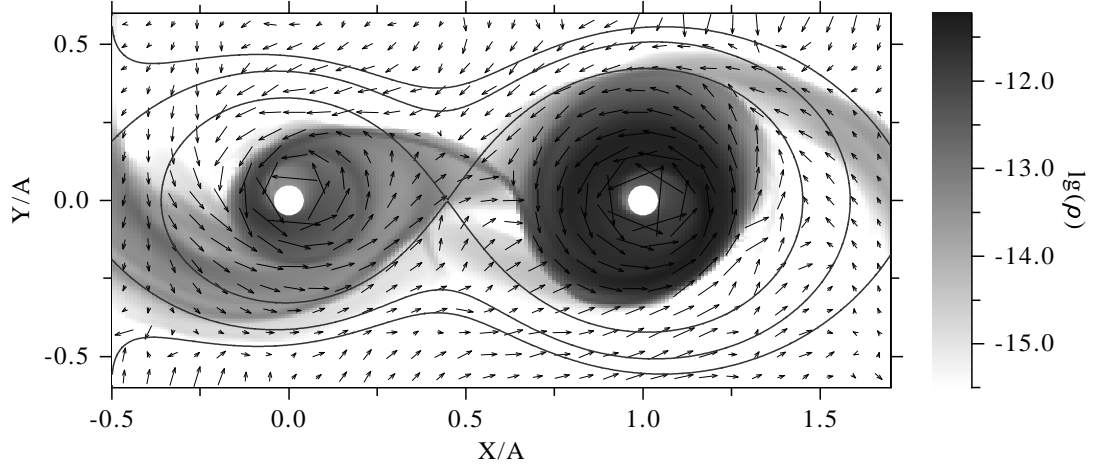


Figure 2: Density and velocity distributions in the equatorial plane near the components of a young binary star. The binary rotates counterclockwise. The more massive companion is to the right. The solid curves denote Roche equipotentials.

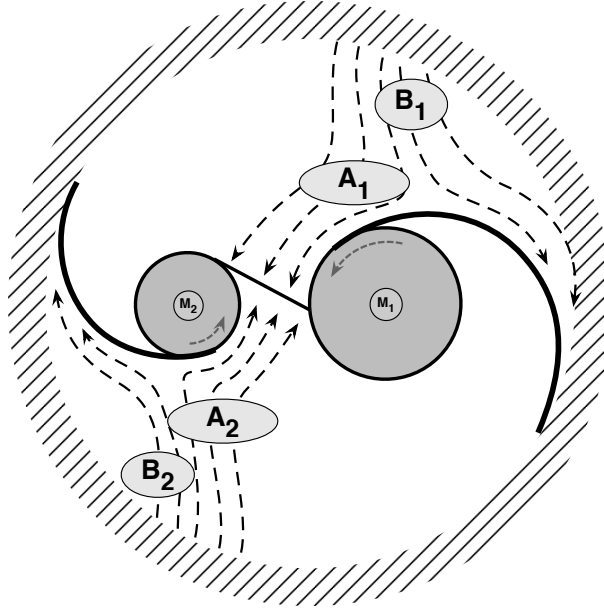


Figure 3: Schematic of the flow structure in the inner parts of a protoplanetary disk around a young binary star that rotates counterclockwise. The primary and secondary are marked M_1 and M_2 . The inner edge of the protoplanetary disk is shown by the diagonal shading. The accretion disks of the components are shown by dark grey circles. Heavy lines denote the fronts of the outward moving shocks that appear as the orbiting components move in the gas of the circumbinary envelope. The dashed curves with arrows indicate the directions of the main flows of matter in the system.

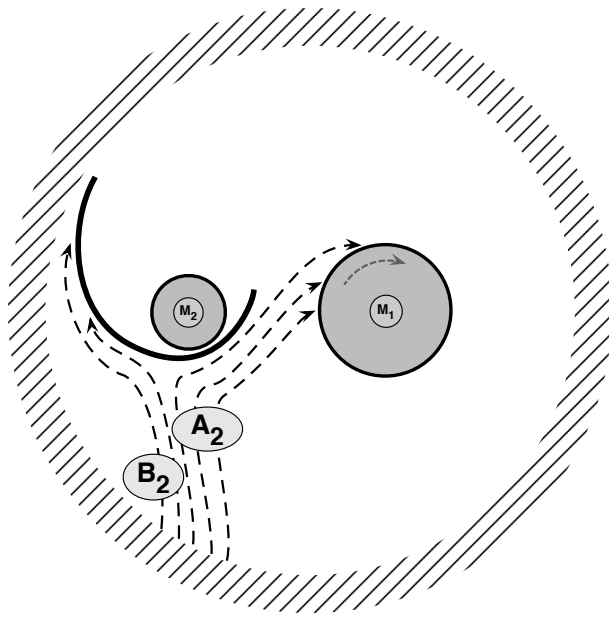


Figure 4: Schematic of the flow structure in the inner parts of the protoplanetary disk around a young binary star with subsonic motion of the primary. The notation is the same as in Fig. 3.